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Framework for the design and evaluation of a reconfigurable production system based on movable robot integration

Amélie Beauville dit Eynaud[1,2] · Nathalie Klement[1] · Lionel Roucoules[1] · Olivier Gibaru[1] · Laurent Durville[2]

Abstract
Enterprises now face a global, dynamic, and unpredictable economic environment. In response to quick changes of the demand, the production needs to have the ability to adapt rapidly to meet the production requirements. The Reconfigurable Manufacturing System (RMS) paradigm enables such capabilities. However, defining design and reconfiguration rules is highly challenging, as it requires a broad knowledge encompassing the inclusion of technological, production, and economic metrics, as well as an understanding of a reconfiguration strategy, determining the necessary reconfiguration frequency of the system. For now, no global methodology taking all those aspects into account has been proposed. This article presents an original framework for the design, evaluation, and reconfiguration of the Reconfigurable Production System (RPS). New metrics to measure reconfigurability are defined. The design approach consists in three main steps which are individually developed. The selection of the appropriated production system is based on the comparison of reconfigurability and productivity indicators. Finally, the reconfiguration strategy is presented. The methodology is applied on a case study from the automotive industry.

Keywords Reconfigurable manufacturing system · Reconfigurable assembly system · Reconfigurability · Design methodology · Decision tool · Discrete event simulation

1 Introduction

The industry faces today a turbulent market. Product demand is hardly predictable, and the quick variations of customer's needs are complex to anticipate. This implies quick product changes and difficulties to cover the demand with a traditional production installation, unable to adjust to unpredicted changes [17]. The production variety pulled by the market involves both product variety and production volume changes. Volume changes imply an adaptation in terms of volume capacity, while product variety corresponds to an adaptation in terms of functionality of the production system.

In this context, the target is an ideal production system, able to follow changes of the market regarding product variety and volume, including during the ramp-up phase [22].

Previous manufacturing systems paradigms, namely the Dedicated Manufacturing Systems (DMS) and the Flexible Manufacturing Systems (FMS), were respectively designed to be highly productive to manufacture a single type of product in the case of the DMS and to produce predefined product variants of the same family (FMS). Flexibility is framed by limits defined at the startup of the production system [41]. Considering volume adaptation, the DMS is designed for a fixed throughput, and a modification of the takt time requires an interruption of the production for a period of weeks or months. FMS enables some flexibility regarding production volume, but only within pre-defined boundaries. Indeed, FMS is adapted to a relatively predictable economic environment. The Reconfigurable Manufacturing System (RMS), a new production system paradigm introduced by Mehrabi and Ulsoy [37] and Koren et al. [31], aims to cover production demand in a turbulent economic environment [41]. In a similar way, the Reconfigurable Assembly System (RAS) refers to a modular and quickly changeable assembly system [10].

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A glossary is presented at the end of the paper, to summarise those main definitions. This paper focuses on the term RPS, which covers both RMS and RAS [47].

Industry 4.0 encompasses new modelization methods such as Digital Twins, which is a coupling between measured state variables and a model [28, 34]. Morgan et al. [42] present a literature review on Reconfigurable Manufacturing Systems, including Digital Twins. Our position regarding this state of the art is a contribution to the first research question raised, aiming to give a design recommendation for an RPS capable of rapid changes (agile), with increased throughput and decreased cost. However, our approach based on modelling is not a Digital Twin, as there is no feedback loop to a real system. This paper focuses on reconfigurability indicators and RPS Design methods.

Since the initialization of the RMS paradigm, the research area has been widely documented [2]. The topic reconfigurable system design has been tackled by means of a participatory design method [3], from an architectural point of view [9] or using cladistics [26]. Complementary to previous works, this paper aims to propose a global methodological framework aiming to support design, evaluation and reconfiguration of RPS by integrating movable robots.

Companies need support through all steps of the implementation of an RPS: identification of reconfigurability level and needs; choice of the right decision level and associated technological bricks; configuration and layout choice; reconfigurability strategy choice. Companies' awareness regarding flexibility and reconfigurability increased in the last years. Nevertheless, there is still a need in guiding enterprises in order to ensure acceptance of new paradigms and recognition on long-term return on investment [5]. Furthermore, Glock and Grosse [22] underline the lack of consideration of interlinked problems covering capacity investment and resource assignment and performance measurement.

RPS paradigm is part of Industry 4.0, and belongs to Smart manufacturing systems [45], and is enabled through new technologies, such as Cyber Physical Systems, collaborative robotics, Automated Guided Vehicles (AGVs) [6, 16], and Mobile Robotic Platforms for manufacturing and assembly [21, 34]. However, considering the current state of development of these technologies, and the lack of safety regulations to cover human-machine collaboration, it is not possible to implement them today for mass production. This is why the study is based on the hypothesis of technological maturity of aforementioned bricks implying security, safety norms, vision systems, mobile platforms, and a global development implying a decreased price of this new type of equipment.

Figure 1 illustrates the objective of the design approach introduced in this paper. The initial situation is an actual system which is either highly productive, but fixed (robotic cell), or very flexible and reconfigurable but less productive (human worker). The objective is a reconfigurable system which will enable to have a system with both capabilities: productivity and reconfigurability. For now, this figure is qualitative. Indicators presented in this paper will enable to reproduce this figure in a quantitative manner, to prove the contribution of our proposal.

After an analysis of relevant literature in Section 2, new reconfigurability metrics are presented in Section 3. Section 4 describes the original design approach, which is divided into three main steps. The best setting of the production system is selected based on reconfigurability, productivity and cost indicators. Section 5 deals with the application of the methodology on a case study from the automotive industry. This paper ends with a conclusion and a proposal for future research in Section 6.

2 Literature review

Since introduction of the concept of reconfigurable manufacturing in the 1990s by Sethi [49] and Mehrabi and Ulsoy [37], RPS principles have been broadened to different topics: design, control, planning, etc. For the definition of a

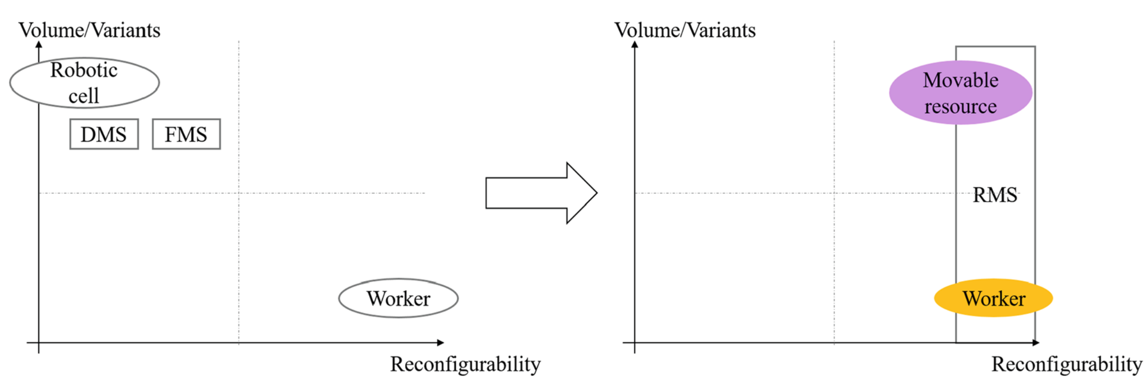


Fig. 1 Actual situation (left) and reconfigurable system (right)

design approach of a reconfigurable system, it is necessary to review the literature on reconfigurability characteristics, design techniques of reconfigurable systems, reconfigurability assessment criteria and reconfiguration strategies.

2.1 RPS characteristics

Flexibility is defined as the characteristic of a fixed system having intrinsic changeable abilities (technology or software) to adjust to various planned and predefined product variants. Beyond flexibility, a RPS is composed of standardized sub-entities enabling rapid production change in terms of volume or product type [38]. It is enabled thanks to production system structure changes. The system can be improved and transformed instead of being replaced [38]. Finally, the objective is to provide a system able to fulfill desired functionalities or production capacities at the desired moment [8].

Koren [30] identified six characteristics of reconfigurability, namely convertibility, scalability, customization, modularity, integrability, and diagnosability. The first three are critical reconfiguration characteristics, meaning that they were identified as key characteristics enabling transformability properties of the production line, and the last three allow rapid reconfiguration, but do not guarantee changeability as presented in Fig. 2 [32]. *Convertibility* refers to the ability of the system to change easily between functionalities in order to respond to new needs; *scalability* is the capacity to rearrange the current production system in order to increment or reduce the production volume; *customization* is the ability to adjust the system in order to meet new requirements within a particular product family; *modularity* is the fragmentation of functionalities into production system units that can be rearranged during production changes and combined in multiple ways; *integrability* is the ability to integrate quickly and easily production elements within the system enabled by physical and software interfaces; and *diagnosability* refers to the capacity to diagnose as soon as possible quality failures and their root causes on the production line, which is a critical point especially during the ramp-up phase [15, 30]. An empirical study conducted by Maganha et al. [35] among more than a hundred of Portuguese companies proved that customization and adaptability characteristics of reconfigurability have a higher level of implementation than modularity, integrability and diagnosability, that are less known or considered yet.

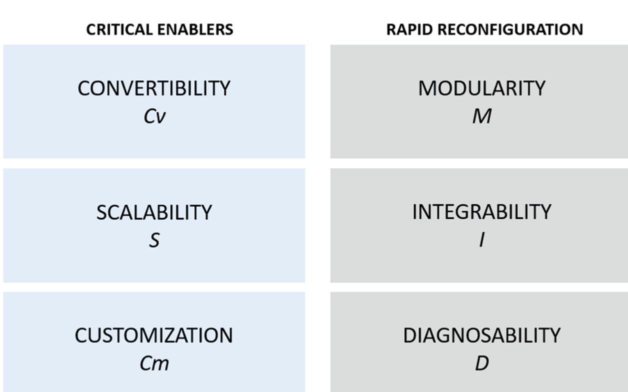


Fig. 2 Reconfigurability characteristics (critical enablers and enablers for rapid reconfiguration)

2.2 RPS design

Designing production systems able to cope with uncertainty is one of the main challenges, with consideration of requirements needed for transforming the system during early design phases [50].

DMS design and RPS design have some common steps: needs specification, functional design, physical design and detailed process design [2, 9]. However, the difference between both lies in the necessity, in a turbulent environment, to take into account the lifespan of the production system on long term, and of the current and future product portfolio.

When designing a production system, two approaches are practicable: design from a blank page or transformation of an existing production system. The first situation enables more freedom concerning resources and layout, while the transformation of a dedicated system into a reconfigurable production line implies limits in terms of compatibility of the new equipment with former installations and control systems.

RMS design has been investigated in the last years. Andersen et al. present in [2] a systematic design method for the flexible and reconfigurable manufacturing line, further developped in [43] . The general methodology is divided in five main steps. Before the design, it is important to have a long-term view on the lifespan of the production system and on the planned investments in mind. The first step is strategic planning, which deliverable is the development plan. The procedure for this first step includes financial optimization, analytic hierarchy processing aiming qualitative analysis of the reconfigurable solution in terms of reactivity, costs, etc. After the project plan has been defined, the next stage is the clarification of the design task, with a focus on identifying requirements and drivers for the RMS. This stage delivers requirements specification, which enables the basic design of the production system. During this step, product families are identified, and the degree and type of reconfigurability are defined. Basic design is then followed by advanced design, where production system modules are developed in detail; this encompasses the definition of system interfaces, tools, and the control system. After managing design specifications, the implementation of the system, followed by line start-up, can begin. The main focus during this last fifth phase is risk analysis. In addition, during the entire lifespan of the RMS, the system may be reconfigured if changes in functionality or capacity are required. The reconfiguration may be a reiteration of the steps of the design phase.

In an other way, Mesa et al. [39], Haddou Benderbal et al. [23], Saliba et al. [48], and Gauss et al. [20] propose each an RMS design methodology based on the evaluation of a modularity criterion.

However, despite the consideration of reconfigurability and modularity in early design phases of the production system, these methods do not take into account the other characteristics of reconfigurability defined by [30], as well as the implementation of tools needed to apply the proposed models. Those point are a strong limit in the stand-alone application of these methods in the industry.

2.3 Reconfigurability evaluation

In order to support RPS design and evaluation, companies are seeking a set of indicators in order to measure the flexibility and reconfigurability level of their facilities and machines [2, 46].

While Key Performance Indicators (KPIs) of production systems are widely documented, there is no consensus yet on the definition of reconfigurability indicators. Researchers do not agree on a metric to measure reconfigurability.

According to Andersen et al. [2], there have been some attempts to measure reconfiguration difficulty in terms of cost, time and effort [54]. Huettemann et al. [27] define evaluation criteria of the RMS according to the production level (segment, line, workstation) and the field (technical resources, organization, and control). These criteria correspond to resource use rates, production throughput, and therefore could be categorized into performance indicators more than indicators concerning system changeability. Mittal et al. [40] evaluate reconfiguration complexity using a unique indicator, named reconfiguration effort, computed by means of the number of modules needed to add or changed in the production system to realize the transformation. It supports product sequence choice, when the product arrival order has a direct impact on equipment reconfiguration.

Reconfigurability indicators calculation methods can be classified into direct techniques, including the measure of the range of products or volume range covered by a system, and indirect techniques, like the performance measure of the system on different volume scenarios [29, 52, 53]. Among direct techniques, Hasan et al. develop a complexity metric, computing the level of part complexity based on sequence and shape features [24]. The authors link the needed scalability of the system with the obtained complexity level. These are quantitative models, but some qualitative models are also discussed. Rösiö et al. propose to evaluate the characteristics of reconfigurability defined by Koren [30] on a four-values scale ranging from 0 to 1, by inviting experts to qualitatively judge the level of their company on each characteristic [46].

Based on the characteristics defined by Koren [30], Wang et al. [51] propose a mathematical model to assess quantitatively the six characteristics of reconfigurability. The value computed for each characteristic depends on the configuration of the considered production system, the number of modules to add and replace, the time needed for reconfiguration, etc. Compared to the qualitative method proposed by Rösiö et al. [46], this quantitative assessment of reconfigurability criteria is more precise. This model is therefore very promising. However, it was defined for a manufacturing system composed of Computerized Numerical Control (CNC) machines, so it has to be adapted in order to be used in the case of an assembly system.

In a literature review on RMS, Bortolini et al. [11] underline following research directions in the field of RMS: development of an objective-based reconfigurability index able to outperform current subjective evaluation approaches, and a generic method to assess reconfigurability in various industries.

2.4 Reconfiguration strategy

After RPS design iteration, the production system is adapted to the current market demand. In order for the system to be optimised in the long run to customer demand in terms of volume and product variability, consecutive reconfigurations will be needed. The ability to notify when a reconfiguration is needed has been underlined [2]. Indeed, a determined reconfiguration trigger is required which is the starting point for next reconfiguration. Andersen et al. [2] highlight the necessity to define a method in order to be able to be aware of the need for transformation during the system's lifetime. According to the authors of [2] and [36], defining a way to express the need for reconfigurability through a metric should be considered in future works.

Brunoe et al. [13] address a notion of reconfiguration frequency, which is supposed to be shorter (on every-day basis) in small-medium enterprises (SMEs) than in large companies (monthly basis). The reason suggested by the authors is that production volumes are higher in large companies than in SMEs. Nevertheless, even if this article is one of the few to address the question of the reconfiguration frequency, it is not sufficient in order to define a strategy.

In an other way, Garbie [19] defines not a frequency but a new indicator, named the Needed Reconfiguration Level (NRL), to guide the reconfiguration decision. Above a threshold value of the NRL, the production system should be transformed in order to meet requirements of the market demand. If reconfiguration is necessary, the method described can be followed in order to determine which modifications should be added. This paper is interesting because it brings a first answer regarding a reconfiguration strategy based on a metric. The drawback of the method is the complexity to implement it. Indeed, some metrics let a lot of liberty and flexibility, which raises the question of robustness of the procedure. Furthermore, intermediate calculations are tedious which restrains a regular use of them. The reconfiguration methodology based on the NRL is decomposed into 30 steps. This can be a drawback when deploying the method in an industrial context.

Boucher et al. [12] identify a four-level tooled methodological framework for reconfigurability management and the successive decision steps for reconfiguration. At each level, aided-decision tools are needed, aiming a life-cycle management of RPS through uncertainty management. Further research needs identified by the authors are the necessity of a tool box for reconfigurability management, covered by this article, and uncertainty modelling and assessment, addressed in [7].

The state of the art on reconfiguration strategy proves that companies lack a reconfiguration method for their production system based on a precise and case-specific metric. However, two strategies can be identified for the production manager to have the information when to reconfigure the production line: either based on a predefined reconfiguration frequency, or based on a metric which triggers a reconfiguration when the threshold value is reached.

2.5 Discussion of the literature review

2.5.1 Methods

In the literature dealing with reconfigurable production system design, it has been identified that no global methodology with practically applicable procedure has been proposed yet. Despite the analysis of the literature brought some interesting insights in the field of RPS design rules, no aid decision tool could be identified. A need for a methodology providing an aided decision tool with quantitative metrics associated to a methodology and a reconfiguration strategy, supported by a case application, has been detected. This paper presents in Section 4 a methodology aiming to fulfill this need.

2.5.2 Reconfigurability metrics

What concerns metrics and characteristics, productivity and costs are well-defined in the industry. Regarding criteria-based reconfigurability evaluation, [46] and [51] works are very promising. The idea of the first paper to define a value for reconfigurability will be kept and enhanced by quantitative calculations, inspired by the mathematical model proposed by the second paper.

Metrics will support the decision maker regarding the choice for the implementation of a technology and a configuration of the assembly line. To do so, indicators have to be defined. To cover productivity as well as changeability properties, reconfigurability indicators have been defined. Section 3 describes the used performance indicators and investments which will be depicted on the dashboard of the aid decision tool.

3 Reconfigurability characteristics

In order to guide the decision maker regarding easiness to transform the production system, reconfigurability indicators are required. As described in Section 2.3, indicators provided in the literature were not satisfying regarding both precision and applicability for an assembly line case. Based on the metrics defined by Wang et al. [51], we propose four new indicators to compute the *scalability*, the *modularity*, the *integrability*, and the *customization*. The formula to compute *convertibility* has not been changed, as it is already adapted to calculate the convertibility level of RAS.

Only *diagnosability*, the sixth reconfigurability characteristic defined by Wang et al. [51], has not been kept for reconfigurability measurement in this study. Diagnosability is not a critical enabler for reconfiguration and is mainly influenced by the technology exploited for detection and diagnosis and the number of diagnostic equipment on the line [30, 44]. In the proposed approach, diagnosis equipment is not considered and not included in models and simulations.

3.1 Scalability

Wang and Koren define the scalability as the smallest incremental capacity of the system [52]. However, this definition does not consider the time and the cost needed for the reconfiguration. As underlined by Cerqueus et al. [14], if a production system is scalable, then reconfigurations are quick, incremental and cost-effective. Thus, our goal was to develop a metric which covers those three aspects. The main challenge is the ratio Time to reconfigure/Takt time, which varies a lot between a fixed system and a reconfigurable system. The same issue occurred for the definition of the customization indicator. The model developed to compute the *scalability* level S of the assembly system is described by the multiplication of a factor expressing the reconfigurability span and the size of the adjustment gradient in terms of volume changeability of the production system, a time and a cost parameter, and an adjustment parameter representing the number of system modules added. The model is developed for a minimum to maximum evolution in terms of volume through reconfigurations, which explains why only the number of added workstations is considered.

Scalability is decomposed into following parameters: λ_T, λ_C, and α_i, defined by Eqs. 1, 2, and 3, respectively. In following expressions, T_{cycle} is the cycle time after reconfiguration, T_{reconf} is the reconfiguration time needed to perform reconfiguration step Δ, C_c is the construction cost of the complete construction instead of reconfiguration, C_r is the reconfiguration cost, N_r is the number of resources added during reconfiguration and N is the number of resources before reconfiguration. Finally, Eq. 4 computes the scalability value.

$$\lambda_T = 1 + 0.1 \ln\left(\frac{T_{cycle}}{T_{reconf}}\right) \tag{1}$$

$$\lambda_C = 1 - \frac{C_r}{C_c} \tag{2}$$

$$\alpha = \frac{N_r}{N} \tag{3}$$

Finally,

$$S = \frac{\Delta_{max} - \Delta_{min}}{\Delta_i} \lambda_T \, \lambda_C \, \alpha_i \tag{4}$$

A higher scalability indicator S indicates a higher capacity incrementation of the assembly system.

3.2 Convertibility

Convertibility is defined as the capability to quickly shift to the production of a different product, within a same product family or between product families [51]. Convertibility is calculated by the computation of convertibility within a product family, that is to say between product variants, and convertibility between product families. Weights ω_1 and ω_2 for the convertibility within a product family and between product families are both set to 0.5.

Wang et al. [51] defined two separated indicators for convertibility within and between product families. Indeed, the cost of convertibility depends on the difference between products. C_1, defined by Eq. 5, is the convertibility of the system within a family. N_p the number of product types in the product family, $2N_p - 1$ is the number of conversions between products, N_t the number of resources that need tool change.

$$C_1 = \frac{2N_p - 1}{N_t} \tag{5}$$

S_c, defined by Eq. 6, is the similarity coefficient between product families. C_2, defined by Eq. 7, is the convertibility coefficient between product families, and N_w the number of workstations that need to be added or removed for the conversion between product families.

$$S_c = \frac{n_{ij}}{x_i + y_i + n_{ij}} \tag{6}$$

N_{ij} : number of workstations used for both products i and j

x_i : number of workstations for product i only

y_i : number of workstations for product j only

$$C_2 = \frac{S_c}{N_w} \tag{7}$$

The formula for the calculation of convertibility for the whole production system is presented in Eq. 8.

$$C_v = \omega_1 \frac{2N_p - 1}{N_t} + \omega_2 \frac{S_c}{N_w} \tag{8}$$

A higher convertibility indicator C_v indicates a higher capacity of conversion between products of the assembly system.

3.3 Modularity

Modularity evaluates the capacity of the system to be split into modules and to integrate them. Equation 9 presents the calculation of system modularity, where G_i is the granularity of the ith workstation, where N_{ij} is the count of interfaces at the jth modular division of the ith workstation, N_{kl} is the count of interfaces at the line level module after conversion k, G_k is the granularity of conversion k, and ω_1 and ω_2 are the weightings of the workstation modularity and reconfiguration modularity (in this study arbitrarily set to 0.5).

$$M = \omega_1 \frac{G_i}{N_{ij}} + \omega_2 \frac{G_k}{N_{kl}} \tag{9}$$

A higher modularity M denotes a higher modular capacity of the assembly system.

The values for the granularity of the workstation and of the reconfiguration are defined in Tables 1 and 2. G_i and G_k range from 0 to 1. Regarding the workstation granularity value, a deeper level in the factory implies a higher granularity value. Concerning the reconfiguration granularity value, the more we zoom regarding the size of the reconfigured element, the higher G_k is.

Table 1 Workstation granularity values

Modular division	Value for G_i
None	0
Workstation	0.3
Resource	0.5
Tool	0.7
Tool module	0.9

Table 2 Reconfiguration granularity values

Modular division	Value for G_k
None	0
Network	0.2
Product flow	0.4
Modular line	0.6
Resource change	0.8
Tool change	1

3.4 Integrability

Integrability is the ability to add components to the manufacturing system using adapted interfaces. We define integrability by means of Eqs. 10, 11, and 12, where P is the number of workstations, N_i the number of modules in the ith workstation, ω_1 and ω_2 are the weightings of the physical equipment and programming adjustment parameters (set to 0.5), T_j^h is the equipment installation and set-up time, and T_j^s is the software installation and set-up time of the jth module of the ith workstation.

$$\alpha_j = -0.1 \ln(T_j^h) + 1 \tag{10}$$

$$\beta_j = -0.08 \ln(T_j^s) + 1 \tag{11}$$

$$I = \sum_{i=1}^{P} \sum_{j=1}^{N_i} (\omega_1 \alpha_j + \omega_2 \beta_j) \tag{12}$$

A higher integrability I denotes a higher capacity of the production system to integrate system components. I ranges between 0 and 1.

3.5 Customization

Customization describes the ability to convert between products thanks to the selection of system components [51]. The mathematical model to quantitatively measure customization C_m is presented in Eq. 13, where P is number of product types in the family, T_{cycle} the cycle time, T_{reconf} the reconfiguration time, N_i the number of workstations used for the ith product, and N the overall number of workstations in the system.

$$C_m = \left(1 + 0.1 \ln \frac{T_{cycle}}{T_{reconf}}\right) \sum_{i=1}^{P} \frac{1}{P} \frac{N_i}{N} \tag{13}$$

A higher customization C_m denotes a higher ability of the production system to convert between product types.

3.6 Display of the reconfigurability indicators

Presented formula enable assessment and comparison of various technologies regarding reconfigurability, based on dimensionless criteria. Results can be normalized and presented on a radar diagram. Wang et al. [51] and Beauville et al. [5] proposed an Analytic Hierarchy Process (AHP)–based evaluation of reconfigurability characteristics weight. This enables to weight reconfigurability characteristics according to their relative importance and to present results on a radar diagram. This may help the decision maker for the assessment of the system and comparison between several equipment solutions.

Weighting of reconfigurability characteristics also enables to merge the six indicators into one. This way, we obtain a reconfigurability indicator aggregating the six dimensions of changeability which enables to compute a single value for the reconfigurability.

3.7 Conclusion

Reconfigurability indicators have been defined to serve design and setting of a reconfigurable production system. A comparison with indicators from the literature is presented in Table 3. Previous works developed criteria which were qualitative, or quantitative and performance-based or based on the reconfigurability characteristics defined by [30], but only suitable for RMS. Proposed quantitative reconfigurability indicators cover a field which has not been handled by the literature before.

Table 3 Reconfigurability indicators comparison

Reference	Qualitative	Quantitative	Performance-based	Based on reconfigurability characteristics	RMS	RAS
[54]		X			X	
[27]		X	X		X	X
[40]		X			X	
[46]	X			X	X	X
[51]		X		X	X	
This paper		X		X	X	X

4 Methodology

Driven by the identified need regarding a global methodology for RPS design, and based on already existing methods [2] presented in Section 2.2, we propose a design procedure which will be detailed in this section. This approach aims to support the industry when designing an assembly line in a long-term investment strategy in a turbulent economic environment. The method supports either design from the blank page or resource addition to an already existing production line.

Based on the analysis of previous literature, our design methodology for the RPS, presented Fig. 3, is divided into 4 steps [5]: reconfigurability needs identification and design task definition, technological choice and system modelling, configuration assessment through simulation, and at last regular system reconfiguration. Each step is detailed in the following sections.

4.1 Changeability needs identification

In order to define needs regarding reconfigurability, the first step of the design method is the identification of company needs. Planning the initial infrastructure for reconfigurability and scalability is crucial, to save space and to have a reconfigurable production system architecture for adding equipment [33]. Design of the reconfigurable assembly line will be defined by identification of requirements concerning future potential economic market changes [5]. For this prospective step, Andersen et al. [3] apply a questionnaire submitted to experts and decision makers within the investigated companies. Several meetings were required to discuss reasons for reconfigurability motivation within the studied company. Questions were precise and divided into sections, depending if the subject was product, production, facility, or technology. The aim was, through the questionnaire, to specify changeability requirements and to determine the relevant manufacturing system paradigm. In a similar way, Maganha et al. [35] complete a survey to explore perception of reconfigurability within companies. Results gave information on the level of flexibility and reconfigurability of their production system and on the future actions they plan in this direction.

Based on the two previous works, the questionnaire used in this study partially reuses questions from [3] and [35]. Answers are either evaluated on a Likert scale or are open-ended questions and concern product characteristics, process and facility characteristics [5]. The aim, through this field study based on a questionnaire, is to open the discussion and raise awareness of the needed changeability capacity of the production system [5]. This approach enables to collect valuable information about

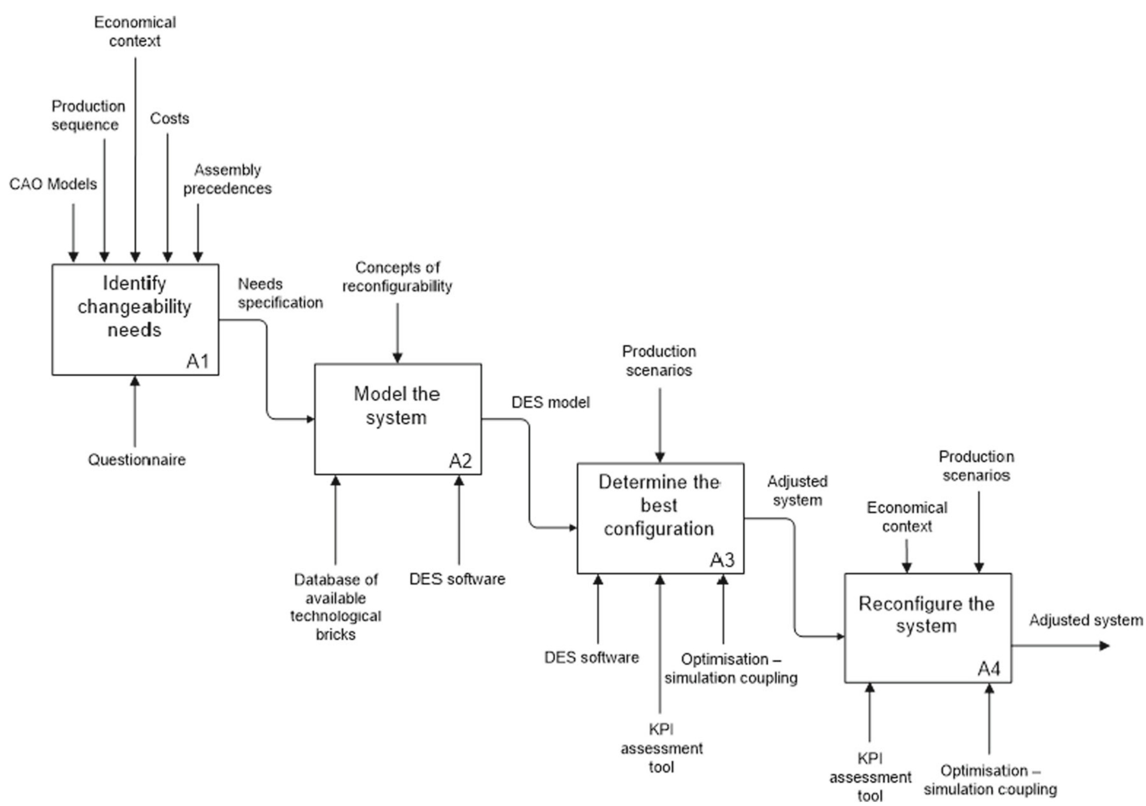


Fig. 3 SADT Diagram of the design approach

reconfigurability development chances within the factory. This depends on the similarity between products assembled on the same line, on the sequencing of products before input on the line, precedences between assembly tasks, on the economical context, and on equipment costs.

At this stage, we mainly collect two types of information: what are the requirements for RPS design, and what are the current enablers and limits regarding reconfigurability within the facility. Specification of needs for a RPS and current limitations caused by facility characteristics, architecture and resources are collected.

After changeability needs identification, a first draft of relevant technological solutions, depending on the production system characteristics and architecture in the case of RPS design from an existing production system, is ready. This provides the needs specification for the modelling of the future production line.

4.2 System modelling

From the needs identified in the first step, required technological bricks are identified. The choice of the technical solution to implement reconfigurability on the line will then feed a simulation. The production system needs to be modelled in order to build a discrete event simulation model. By running experiments on the model, KPI will be measured. In parallel, the amount of investment and reconfigurability indicators of the assembly line can be computed.

From the analysis of the literature regarding reconfigurable production systems and of the technological maturity of Factory of the future concepts, relevant technological bricks are determined. The adopted principle is to propose for RPS design a limited solution domain. That is to say, we do not have the ambition to create new technical solutions, but to propose to pick a solution among a limited set of technologies. The user selects among a general set the resources to implement and test through the design approach.

Identified technological bricks which will be proposed for RPS design cover three axis: the way of transporting the product through the factory, modularity and standardization of workstations and machines, and mobility of resources. The first corresponds to the study of product flow, which can be serial, parallel, or hybrid [52]. Modularity of workstations concerns the workstation level, resource level, and tool level. The third axis can be implemented through the use of an AGV, not only to transport the product, but also to relocate a resource. But as the AGV may not be relevant in the cases where reconfiguration do not occur at a high frequency, it may be enough to place the resource on a movable trolley. Either with the aforementioned mobile or movable solution, resource mobility on the production line is enhanced. For each use case, the paradigm for the reconfigurable assembly line must be determined through the field analysis and technological bricks accordingly selected.

The Discrete Event Simulation (DES) model is developed according to the assembly sequence of the future reconfigurable line. Simulation enables to test scenarios at a low cost and deduce implications for the real production system and allows to vary parameters that may not be manageable in real life [18].

DES provides statistical insights on system's performance and gives information on the dynamic behaviour of the system on a determined structural state of the system [1]. This is why several models are needed in order to assess different technologies.

Simulation requires a model of the production line containing all relevant data: workstations, tasks and their durations, precedencies, resources and failure rates, layout. Failure rates of machines are completed from data measured in factories. The objects in the simulation are represented by activities or servers depending on the used software, resources and product data. The model should correctly represent time and processes. The running time is the time period corresponding to the next planning horizon.

In this second step of the design methodology, as the technological bricks and their number are defined, it is possible to compute the amount of investments for the configuration of the RPS.

Manufacturing resources investments reflect the purchased resources. Worker costs are not represented as it is complex to represent on the same scale investments and running costs like workers' salary, energy cost of the production line, etc.

To be able to compare technical solutions on a financial criteria, investments are be depicted as function of time. The goal is to highlight the difference between a very early investment and acquisition of the resources at the right time when it is needed. The cost is required by decision makers to compare a new solution with the existing one regarding return on investment ratio.

4.3 Configuration determination

For the third step of the design approach, the DES model is used to assess the system in terms of productivity.

The objective is, through the selected performance criteria, to measure the efficiency of the designed production system.

Selected Key Performance Indicators are the number of assembled products within the simulated time interval, lead time, and machine/resource use rate, which depicts the non-use time due to forced shutdown, breakdown and waiting time. Manufacturers are familiar with these metrics as these are the same as the ones used in production.

The proposed aid decision tool underlines the articulation between performance criteria, reconfigurability criteria, simulation. Charts are represented on a dashboard which serves the choice based on a compromise between ability to reconfigure, performance of the system and price of the solution. For the simulation model, a scenario corresponds to a product mix ratio and a volume, in the range of sales prediction uncertainty. By comparing provided data, the decision makers is able to choose between different technical solutions.

For the implementation of mobile resources, it is necessary to allocate resources to workstations through an optimization method, minimizing the makespan (total time to finish all jobs). Exact methods are employed to find an exact solution to small size problems, while approached methods, like heuristic algorithms, should be used for non-deterministic polynomial time problems (NP-hard problems). To assess a solution provided by the algorithm, setup parameters can be used as input of the simulation model. After a simulation run, performance parameters of the configuration are obtained and can feed as input the optimization model. Hashemi et al. [25] deals with the coupling between optimization and simulation mentioned in step A3 of the approach presented Fig. 3.

In conclusion, after the third step, the decision maker obtains an optimised setting solution of the studied production line.

4.4 System reconfiguration

The state of the art presented Section 2.4 demonstrates a lack of methods to measure the right reconfiguration period.

We distinguish two main reconfiguration strategies: frequency based strategies and metric-based strategies. In the first situation, independently of the economic context, the production system settings will be verified at a pre-defined frequency. In the second way, the decline of a metric above a threshold, highlighting the system's incapability to fulfill market's needs, will generate a reconfiguration. The company may tolerate a deviation for a short period of time, and decide to launch a reconfiguration if the critic situation lasts.

We recommend to adopt the metric-based reconfiguration strategy. However, to choose the right threshold value and the allowed time window may be complex. The reconfiguration strategy is case-specific and is to be determined after discussion with experts and decision makers from the studied enterprise.

5 Case study

The developed methodology has been applied to an industrial case from the French automotive industry. The ability to transform the production system is particularly relevant in this type of industry, where market changes can occur quickly due to political and environmental regulations, seasonality, and are sensitive to the economic health of countries.

The investigated production scenario is presented Fig. 4. We study the ramp-up of an engine assembly line, composed of twenty workstations, for the two first years of production. The ability to react to strong volume changes will be investigated in this scenario. Depending on the targeted volume, the number of resources will have to be updated quickly to avoid non-fulfilment of the market demand. In this case study, chosen assumption is to build the new assembly system from a blank page, instead of adapting the old system.

5.1 Design approach

The four steps of design approach presented in Section 3 are applied on the industrial use case.

5.1.1 Changeability needs identification

The first stage corresponds to the changeability needs identification and design task definition. During a field analysis, eight experts coming from various fields of the investigated company have been interviewed individually [5].

Answers highlighted expectations for an increasing number of product variants and volume uncertainty over the next years, justifying the need to have a more reconfigurable and flexible assembly system. Besides, a lack of expansion capability of the current assembly lines has been reported. Some factories are already fully charged and can not cover the increasing market demand. Interviewed also mentioned a deficiency concerning aging automatons that

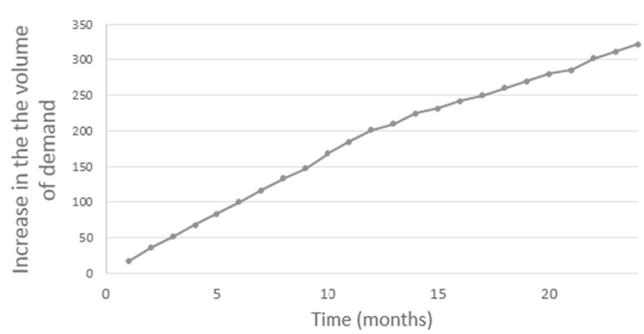


Fig. 4 Ramp-up scenario of the demand

lack in standard architectures, interfaces and programming languages in order to integrate easily and rapidly new equipment. On the other side, the field study reported that the presence of some manual workstations on the assembly line will enable the introduction of light collaborative robots to increase the efficiency of these workstations. The line is already flexible, as different types of product variants within the same product family are assembled and AGVs are used for the transport of product kits, also increasing the flexibility of the plant. After this analysis, it seems that the case company is familiar with the FMS paradigm and now needs to increase the reconfigurability ability of the assembly line. Detailed results of the field study are presented in [5].

5.1.2 Technical features choice and system modelling

Previous section enlightened a need to improve the ability to increment the production capacity and the system's modularity. This statement oriented the choice to a modular solution with quick plug and produce capability. As conclusion of step 1, and based on the bricks identified in Section 4.2, the relevant technological brick to implement is the movable robot. The movable robot is not dynamically mobile during a production shift, but it is placed on a easily movable trolley which position can be changed between workstations. For a first analysis, we will only analyze the relevance of implementing movable robots on the line. To do so, an assembly system with fixed resources will be compared to an assembly system where lightweight collaborative robots can be easily moved between workstations by means of a trolley.

After selection of the technological feature to be implemented, its reconfigurability characteristics are computed and compared to the current production system (Fig. 5). The actual assembly line, a combination of both special machines and fixed robots, is compared to the solution based on movable robots. Reconfigurability characteristics of special machines and fixed robots are very close. The analysis of the reconfigurability based on the five indicators presented in Section 3 highlights that building the same assembly line with movable robots in place of fixed robots or special machines will increase significantly all reconfigurability metrics. Especially, the scalability and the modularity of the system are improved. This result is consistent with the fact that the movable robot consist in a module, easily plug-and-play on the production line. The reconfiguration time is shortened and increases the ability to increment the system in capacity.

5.1.3 Configuration determination

The pilot assembly line is modeled using the DES software Simul8 2019 Version 26.0 Build 3677.

The objective of the third stage of the approach is to measure the performance of the system depending on the evolution of the market demand. The twenty assembly stations of the engine assembly line are simulated. Each workstation is composed of several tasks requiring resources. For example, Fig. 6 presents the precedence diagram of tasks in workstation 2 and Table 4 presents

Fig. 5 Evaluated reconfigurability characteristics

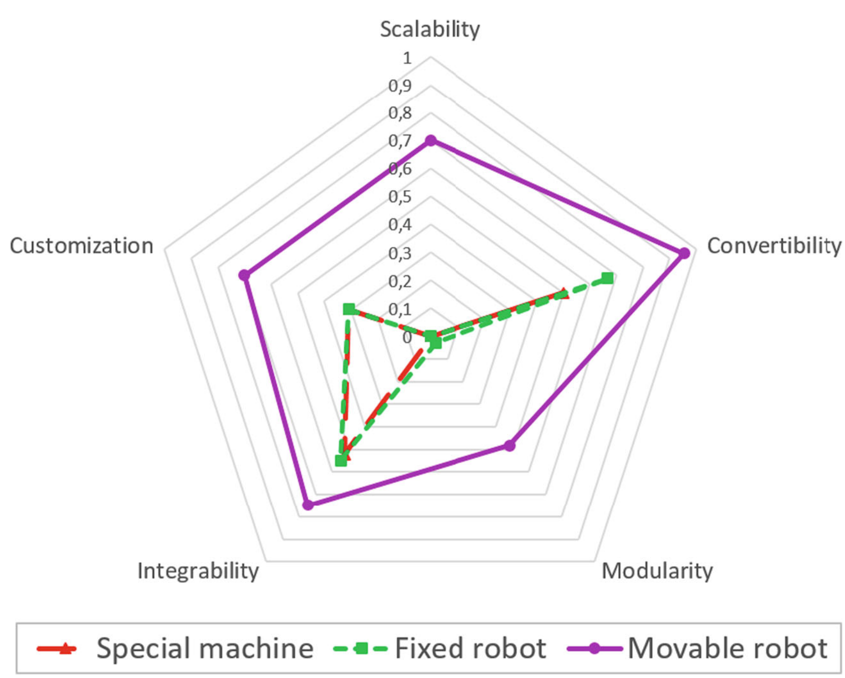
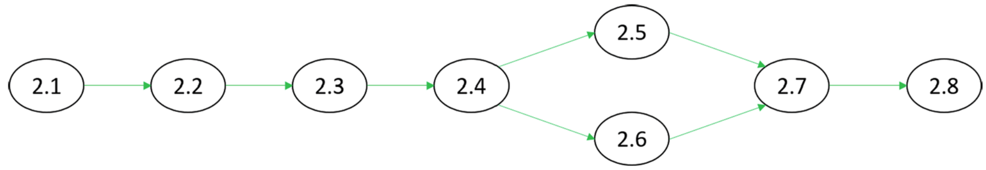


Fig. 6 Workstation 2: precedence diagram



durations of tasks and precedencies for the assembly of a gasoline engine. Precedences between assembly tasks are fixed and considered as inputs of the model.

For the ramp-up scenario, ramp-up is simulated month by month. Each simulation trial launches 3 simulation runs of the model.

In Simul8 environment, each task is modeled as an Activity, and buffers between workstations as Queues with a maximal filling rate of 1 product. The Mean Time Between Failures (MTBF) follows a normal distribution with a mean of 7450 min and a standard deviation of 200 min, and the Mean Time To Repair (MTTR) follows a normal distribution with mean of 2 min and a standard deviation of 0.5 min. Those values are based on measured breakdowns on the company's assembly lines. Table 5 summarizes experimental factors (inputs) and results (outputs) of the simulation.

Figure 7 plots the resource utilization rate from month 5 (time when the first robot is introduced in the reconfigurable model) to month 12 for the fixed system and the reconfigurable system with movable resources. In average, the resource utilization rate is higher for the RAS than for the fixed system, and the reconfigurable system uses less resources. This is better, because purchased resources should be used at their maximal rate if possible, in order to have the shortest return on investment. In addition, reconfigurability indicators are strongly better when integrating movable robots, which indicates that future reconfigurations will be conducted with less effort, and investments are three times lower. By means of all these indicators, decision makers will prefer the RPS for this use case.

5.1.4 Reconfiguration strategy

The reconfiguration trigger has been defined after discussion with experts of the use case company. The threshold has been fixed to a resource use rate of 95 %. In a ramp-up phase, when this limit is reached, a resource should be added on the production floor.

Based on this rule, movable resources were added one by one when required. Figure 8 is a schema of the reconfigurable line a the beginning of the ramp-up (a) and after 24 months at the end of the ramp-up scenario (b).

The reconfiguration strategy adopted in a scenario of decrease of the demand also relies on the use rate of resources. The degree of acceptance is a minimum of a 80% load, and a duration of maximum 3 months under 80%. Practically, if a resource is charged less than 80 % of its capacity beyond 3 months during a phase of volume decrease, this resource can be removed from the assembly line.

5.2 Discussion

Taking into account changeability requirements at early stages of the design process significantly increases chances to achieve a high level of reconfigurability potential.

Figure 9 displays the amount of investments for the fixed system and the reconfigurable system obtained by

Table 4 List of tasks (workstation 2)

Station	Task	Relative durations	Precedences
2	2.1	1	
2	2.2	5.6	2.1
2	2.3	1.9	2.2
2	2.4	3.8	2.3
2	2.5	1	2.4
2	2.6	1.1	2.4
2	2.7	3.8	2.5 ; 2.6
2	2.8	1.5	2.7

Table 5 Summary of experimental factors and outputs

Experimental factor	Output
Task sequence	Throughput
Machine breakdowns	Resource use rate
Product inter-arrival time	Lead time

application of the proposed design approach. On the graph, the relative costs concerning the fixed system and the RPS are represented, as well as the relative operating costs, which corresponds to the workers' salary (same for both systems). Actual production starts at t = 0. Two aspects are noticeable: for the RPS, investments are lower and are carried out at the latest. The solution proposed by application of the method enables adaptation of the system regarding its volume capacity. On the studied ramp-up scenarios, movable resources are integrated on the assembly line at the right time.

The design approach covers design, evaluation and reconfiguration of reconfigurable assembly systems. Figure 1 depicts qualitatively the target of the approach. Thanks to the developed indicators and performance measures obtained by simulation, we are able to display this graph with the results of the method. Figure 10 compares, after running the two-years scenario, the actual fixed system and the proposed reconfigurable system for the assembly line of the case study. The abscissa is a measure of the reconfigurability, calculated as the sum of the scalability, convertibility, modularity, integrability and customization. On the ordinate, the *capacity utilization* is plotted, as ratio of the market demand over the installed capacity. As long as the market demand is fulfilled, the equipment rate will be less than or equal to 1. This metric, relevant in the case of volume reconfigurability, is equal to 1 if the system is able to adapt in terms of volume to the production demand exactly in real-time without excess. In practice, in this case study, the capacity utilization will never reach the value 1. Indeed, the structure of the assembly tasks sequence and tasks allocation between workers and robots imply that resources are not used at 100% of their capacity. However, the revision of the assembly sequence is not in the scope of our study.

Figure 10 enables a simplified rating of the system on only two parameters. The development of the method and associated tool aims at covering the identified need

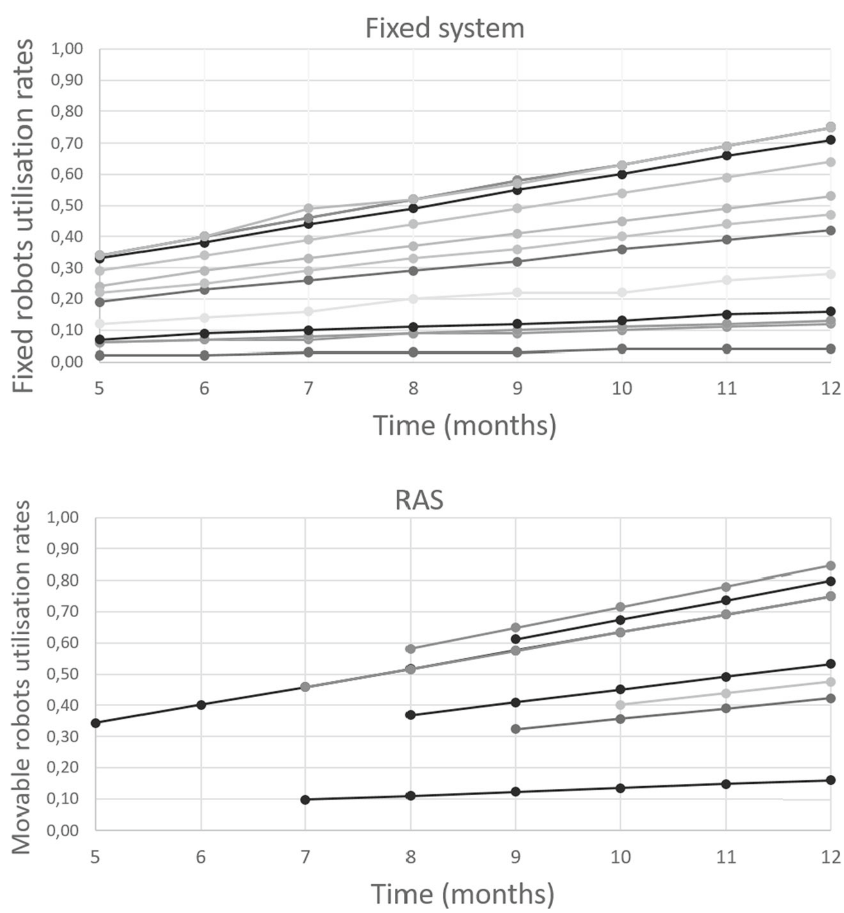


Fig. 7 Robots utilization rates for the fixed system (above) and the reconfigurable system (below)

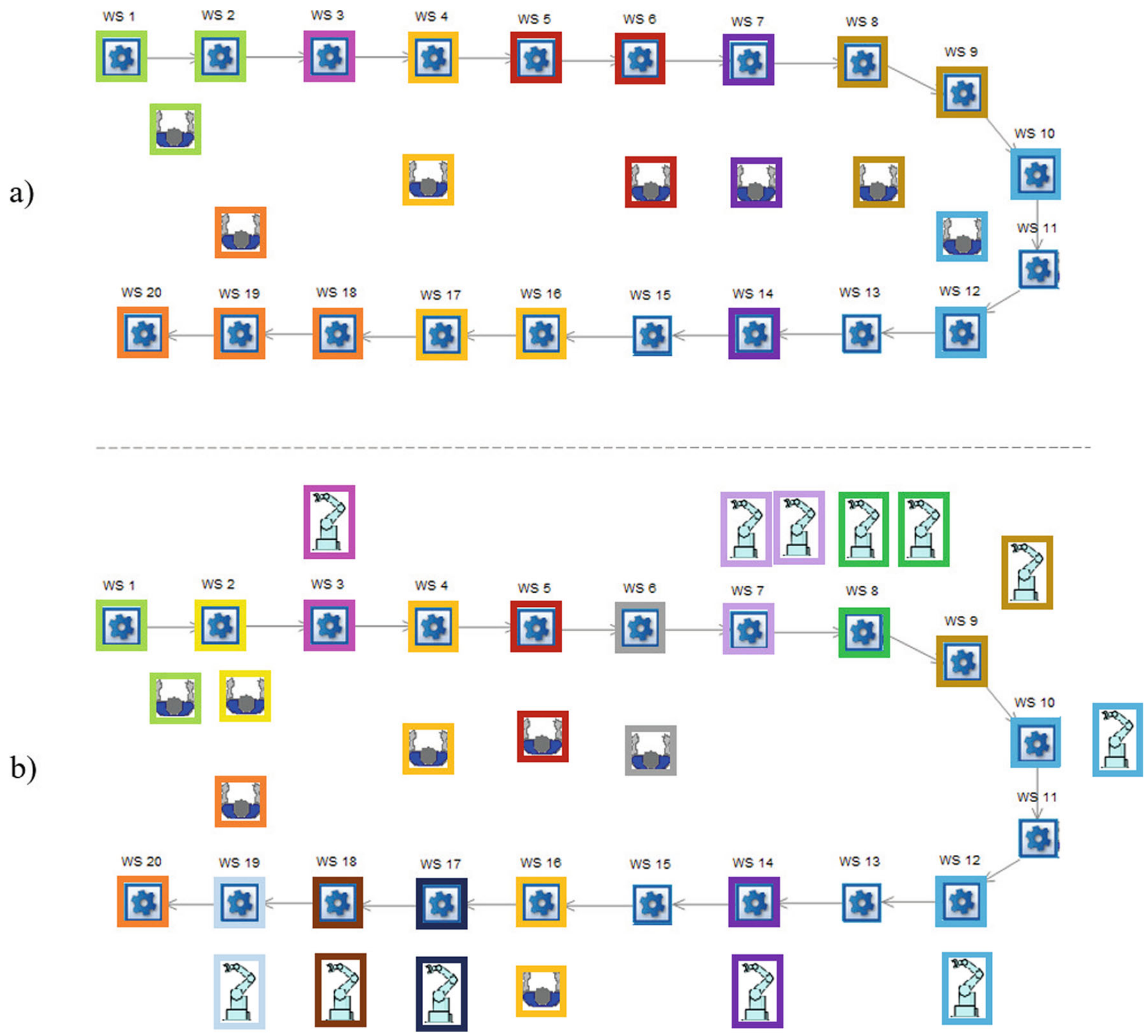


Fig. 8 Schema of the reconfigurable line (a) at the beginning of the scenario (b) at the end of the ramp-up

Fig. 9 Comparison of investments with and without the proposed methodology

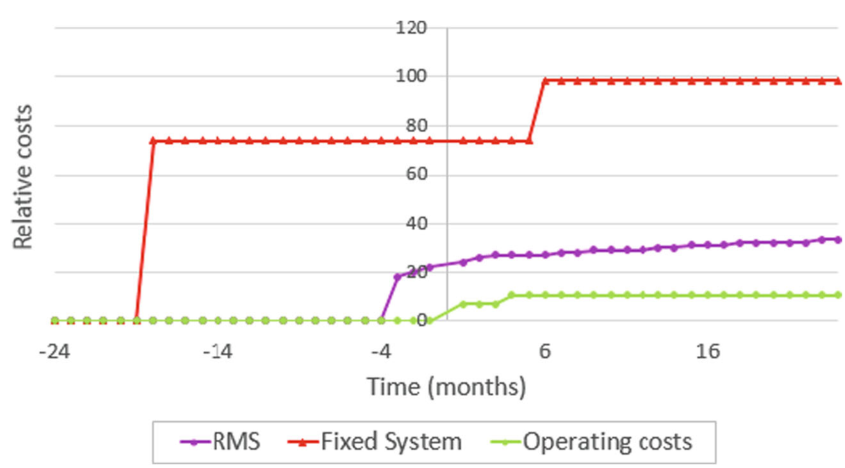
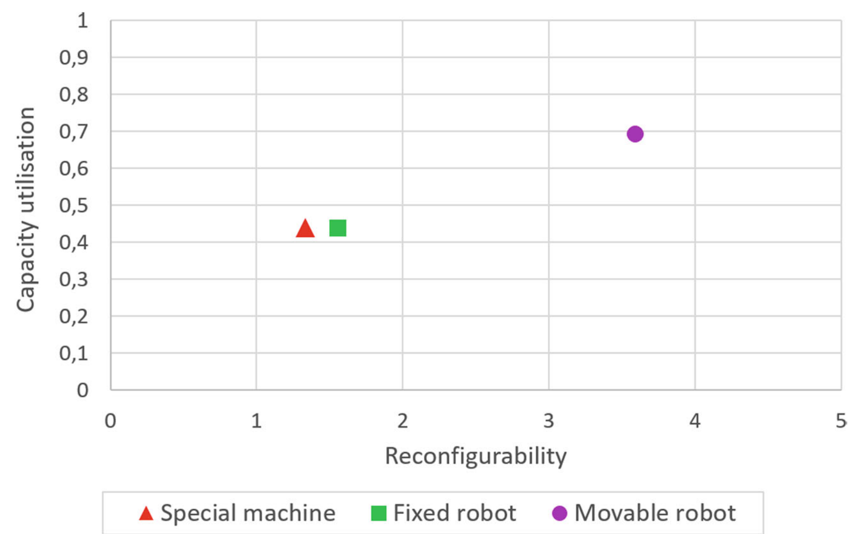


Fig. 10 Rating of technical solutions



of a comprehensive and global approach for the industry supporting reconfigurable systems design.

6 Conclusion and future works

This article presents a new framework for the design and evaluation of a reconfigurable assembly line, based on previous literature. The methodology was applied successfully on a use case from the automotive industry, consisting in a production line of twenty workstations. To provide comparison between technologies and layouts for companies, new reconfigurability metrics were defined. Solutions are compared on the basis of reconfigurability, productivity and investments. For the presented use case, the method leads to savings, with a higher use rate of resources and a more accurate investment timing. In addition, the overall system has a higher reconfigurability rate, facilitating future changes.

To enhance the comprehensiveness of the score given to a configuration of the production system, an interesting suggestion would be to integrate a maturity indicator of technologies enabling reconfigurability. Indeed, the changeability potential is considerably improved by integration of new agile technological bricks, and the success of the solution in a real production environment strongly depends on the robustness of the solution. As we do not have enough hindsight on technologies involving collaborative robotics, mobile entities and modular production systems, the integration of a maturity indicator could temper the very good results of changing a traditional production system into a reconfigurable one.

After the study of a scenario with volume reconfigurability, the methodology will be applied on a production scenario involving different product types. In parallel, links between modules of the approach (reconfigurability assessment tool, simulation model, dashboard) will be developed, in order to achieve a semi-automatic procedure for the design of a reconfigurable manufacturing system. Simulation-based multi-objectives optimisation could be used to explore the best near-optimal pareto solutions among all scenarios that we could investigate [4]. In addition, further research would be required to enhance the modelization of the RPS in order to achieve a Digital Twin coupling. Scenarios would be played in the Digital Twin model, and the best solution as a compromise of reconfigurability, productivity and investments could be implemented. The outcome would be a possibility to achieve RPS reconfiguration through an information flow going from the digital model to the production line. The methodology can also be applied on use cases from other industries.

Glossary

DMS : The Dedicated Manufacturing System is designed to be highly productive to manufacture a specific type of product at a high, fixed throughput by means of automation and fixed manufacturing facilities [2].

FMS : The Flexible Manufacturing System is designed to produce a pre-defined range of products variants, using intrinsic hardware or software capabilities [2, 41].

RMS : The Reconfigurable Manufacturing System aims to cover production demand in a turbulent economic environment, by means of rapid structure changes of the system. The RMS is made of modular sub-entities (hardware and software components), that can be quickly and easily rearranged or replaced [31, 37, 41].

RAS : The Reconfigurable Assembly System refers to a modular and quickly changeable assembly system [10]. The term is similar to RMS but refers to assembly lines instead of manufacturing centers.

RPS : The Reconfigurable Production System is a generic term grouping RMS and RAS definitions.

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Author contribution Amélie Beauville dit Eynaud carried out the experiment. Amélie Beauville dit Eynaud wrote the manuscript with support from Nathalie Klement and Lionel Roucoules. Olivier Gibaru and Laurent Durville supervised the project.

Data availability Data is available on request from the authors.

Code availability Code is available on request from the authors.

Declarations

Conflict of interest The authors declare no competing interests.

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